Temporal modelling consideration for geospatial data to support time-aware operations

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Key words: Time-aware, valid time, standardized temporal description, Interoperability

SUMMARY

The success of GIS heavily relies on the correct use of diverse built-in operation modules. While the design of every operation has its intended purpose and limitations, the temporal aspect is unfortunately often overlooked during operation design. The time-aware operations in this paper imply those operations whose results must depend on the correct availability and interpretation of temporal information. Since the world phenomena may continuously change, the content of geographic data is only regarded as the situation at a specific time, such that all operations involving the processing of multiple datasets with different valid time are potentially time-aware operations. Whether and how time information is recorded, as well as how its topology is determined, will limit the subsequent analysis and applications of geographic data. For time-aware operations, two requirements must be considered, standardized temporal modelling based on the valid time concept and workflow redesign of time-aware operations. One important argument is the GIS operation outcome must also has its own valid time. We first explore 5 factors that must be considered for designing standardized time description, then further analyze the time-aware characteristics of 4 commonly used GIS operations and propose refined design strategies for determining the valid time of the operation outcomes. Meanwhile, the proposed system should be able to visually present the analyzed results for decision making. The preliminary results show the proposed time-aware GIS operations are not only advantageous for providing useful reference information, but even necessary for making correct decisions. Mandatory requirements on the availability of standardized valid time information must be enforced while designing the geospatial features. As the sharing of geospatial resources become increasingly popular, we demonstrate in this research even the most commonly used GIS operations may require brand new design strategies about temporal information to deal with the seemingly simple data integration issue.

SUMMARY

成功之 GIS 操作在很大程度上取決於對各種內建操作模組之正確使用。即使大部分之操作在設計時皆具有其最初之目的及局限性，但不幸的是，在操作設計的過程中，時間方面往往被忽視。本文中之時間感知操作意味著 GIS 結果必須取決於時間資訊之正確可用性及解讀的操作。 由於現實世界之現象具有不斷變化之特性，地理資料之內容僅為特定時間之情形，因此，涉及處理具有不同有效時間的多個資料集之所有操作都屬於時間感知操作。時間是否紀錄、如何記錄以及其位相關係如何確定皆限制後續之分析及應用。對於時間感知操作，必須考量兩個要求，基於有效時間概念之標準化時間模型及時間感知操作之工作流程必須重新設計。 GIS 操作結果必須具有有效時間是本研究重要之論點之一。 我們首先探討了設計標準化時間描述必須考慮的五個因素，然後進一步分析了四種常見 GIS 操作之時間感知特性，並提出了確定操作結果有效時間之改進設計策略。同時，本研究所提出之系統能夠直觀地呈現分析結果以供決策。初步結果表明，改進後之 GIS 操作不僅有利於提供有用之參考資訊，甚至對於做出正確決策也是必要的。在設計地理空間圖徵時，必須強制執行對標準化有效時間資訊可用性之要求。隨著地理空間資源之共享變得越來越流行，我們在這項研究中證明，即使是最常用的 GIS 操作也可能需要全新之設計策略，以處理看似簡單之資料整合問題。

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1. Introduction

Since the environment we live in is not static, the ideal geographic information must record not only appropriate time description, but also update accordingly, such that it can provide correct reference to the world phenomena in GIS-based applications. From a modelling viewpoint, space, time and attributes are the three major elements that constitute geographic data. Geographic data is defined with respect to the data model chosen. The integration of data from different resources must therefore consider the correct modelling and interpretation of time information to ensure the outcome is meaningful as far as the valid time is concerned. This paper argues those GIS operations require temporal consideration, defined as time-aware operations, must be redesigned with standardized temporal information, such that users will be aware of the time issues in their operation outcome to avoid wrong decision making.

As the content of geographical data can be regarded as records at a specific time, an essential requirement for geographic data design is to include a temporal attribute and develop a strategy to correctly record its valid status. Armstrong (1988) proposed that spatial databases should take time into account, and suggested a framework for integrating time with its evolutions in spatial databases. From the late 1990s to the early 2000s, many approaches have been proposed with different consideration, Liu et al. (2006) summarized four main spatial-temporal database models, space-time cube (Kraak, 2003), snapshots(Peuquet, 1999), base state with amendments(Nan, Renyi, Guangliang, & Jiong, 2006), and space-frame composite models (He Weixin, Chen Yiru, & Liu Qihui, 2004). Many geographic data nowadays come with time recording information. For example, the coordinates determined by GPS always come with time information, so as to meet the applications demands of dynamic information (Li et al., 2010). In recent years, the observation data from the rapid growth of Internet of Things (IOT) also inlcudes the information of phenomena time (i.e., time of observation) for describing temporal status of the observation values (Radhakrishna, Kumar, Janaki, & Aljawarneh, 2016). Despite this increasing trend of adding temporal inforamtion to geogaprhic information (often automatically), how temporal information is used in GIS operations is nevertheless rather limited unless the developed applications have a clear objective to highlight the time difference of datasets (e.g., change detection). Hui(2021) combines the characteristics of big data, large-scale and long-term map data and grid topology data, to enhance the GIS system in terms of temporal services and data storage (Hui, 2021).

One of the major missions of cadastre systems is to support the administration of land. Since many operations will trigger the the changes of property rights, time information plays an important role for describing the valid status of the administrative units. For example, when a person sells his land to another person, the status he owns the land is no longer valid and the time this status ends must be recorded. Without time inforamtion, the adiministration mechanism will become chaos. Even for spatial operation like boundary verification, subdivision, and consolidation cause changes, time information is necessary becasue the valid status change after the operation. Regardless of providing current or historical cadastral information, time information must be always considered. When integrated with other sources of data, time information is necessary for determing if the selected datasets can work together. How the GIS functions responde with the heterogenity nature of data content remains a challenge. For example, map overlay often deal with a number of data layers with different levels of abstractions, quality and even collected time. While the overlayed outcome are illustrated and manipulated as a map, its design strategy does not consieder the time difference issue of selected datasets. Although this does not necessarily mean the outcomes are always wrong, not knowing where the risks are is even more scary. This research hence intend to introduce a new temporal perspective to the GIS operation design.The remainder of this paper is organized as follows, section 2 describes the related work of time-aware operations development, including the design of time attributes, applications that incorporate time, and aware operation. We then introduce our approach with the analysis of standardized time description, charcteristics of time-aware operatons and desngn strategies in section 3. One case is discussed in section 4. Finally, the conclusions are summrized in section 5

2. Related Work

Spatio-temporal data is data that include contents of both time and spatial information. Temporal schema in ISO 19108 (ISO, 2002) provides a common reference to the time description of geographical data, where the geometry of time can be represented by either a time instant or time period. The recording of geographical phenomena is often the status at a particular time. Data collected at different time may be managed as versions and can be linked via identification information.

Many GIS applications come from the integration of cross-domain information to reconstruct and describe the state of time and space. Especially for applictions that involve historical data, to assess the time status of selected datasets is necessary. In the current development and popularization of media networks, one of the important characteristics of social networks is that they change over time (Tylenda, Angelova, & Bedathur, 2009). Location-based social networks (LBSN) provides users with many important location-aware services, and many researches indicate that time information significantly affects users' check-in behaviors. Point-of-interest (POI) recommendation is one of its application services. Since users tend to visit different places at different time in a day. Yuan et.al. (2013) consider the time dimension to develop POI recommendation method (Yuan, Cong, Ma, Sun, & Thalmann, 2013). Many studies have demonstrated the consideration of time can improve recommendation performance, and then develop time-aware recommender systems (TARS)(Campos, Díez, & Cantador, 2013). Zhang & Chow (2015) proposed a probabilistic framework for the related research, which uses time-influenced correlation for time-aware location proposals, called TICRec (Temporal Influence Correlations for time-aware location Recommendations)(Zhang & Chow, 2015).

Qualiy-aware resesarch intend to add quality consideration to the GIS operation design, such that users will be aware of the negative impacts due to lack of quality informaton(). Based on varous types of standardized data quality information, GIS operations were redesigned to present visual clues about the quality of the operation outcomes (Su Yuting & Hong Junghong, 2015). Hong (2016) proposed an innovative interface in GIS system called VISA (Virtual Layers, Informative Window, Symbol Transformation, Augmented Table Of Content), which integrates quality considerations into the operation design of the geographic information system, so that the operation can automatically evaluate the quality of the results,

3. The Framework of Time-Aware Operations

The design framework of the time-aware operations is illustrated in Figure 1. Ideally speaking, all datasets are required to include a standardized time description to indicate their valid status. GIS operations are then examined according to their intended outcomes to determine if temporal aspect must be additionally considered. If so, the operation design strategy must be modified by adding the capability of automatically detecting and handling the temporal difference between the selected datasets. Finally, the interface must smartly present intuitive and meaningful interpretation of the outcomes to the users, e.g., auxiliary visualization information. The design approach is similar to the concepts of the quality-aware research mentioned in the last section, only the knowledge about how time aspect impacts the outcomes are the major concern instead.

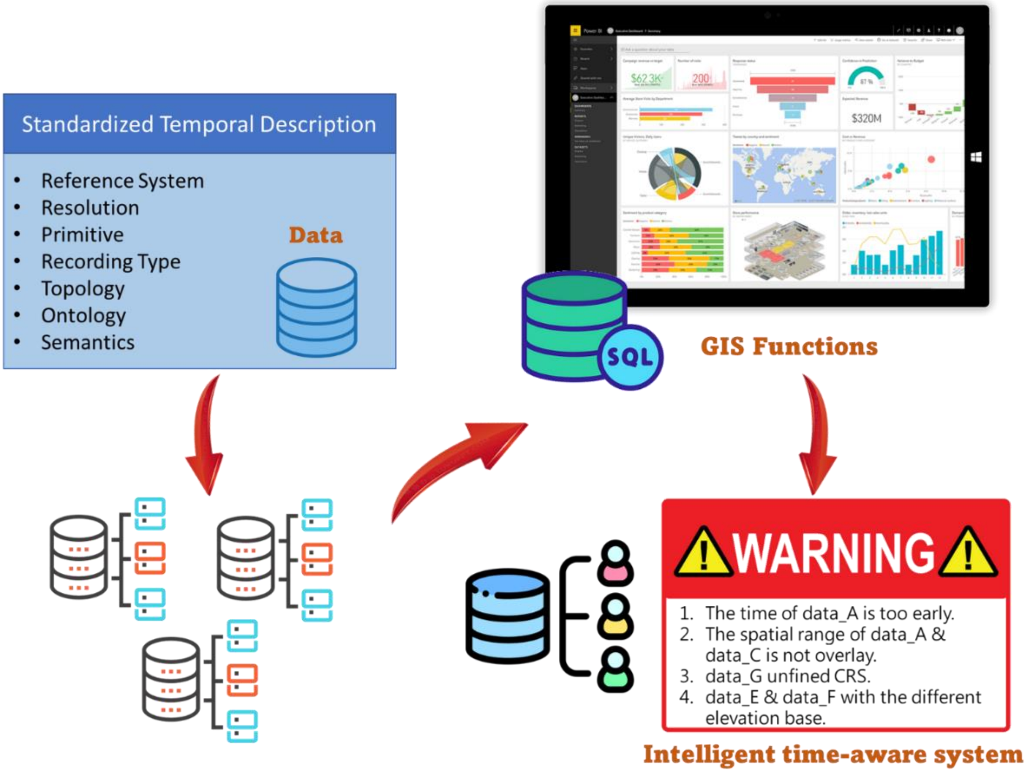


Figure 1. The Framework of Time-Aware Operations.

3.1 Standardized Temporal Description

The design of standardized time descriptions must consider various types of demands. As GIS operates on the content of the selected datasets, the most important consideration is to determine and record the temporal extent where the data content is valid. This implies if we intend to use the dataset in an application outside its valid temporal extent, the data content may be no longer true and the risk of wrong use increases. For example, if we are planning a route, using a road network dataset two years ago certainly hides unpredictable risk due to the new/abandoned roads or even traffic rule changes. The following lists the suggested design factors:

a. Time reference system

For precise comparison, the time information of the datasets must refer to the same time reference system. A time reference system includes two types of information, calendar (e.g., date) and temporal system (e.g., time). The combination of date and time information constitute a unique representation in the 1-D time axis. Despite the system of common era has been widely used globally, many countries continue to use their own time reference systems. It is therefore necessary to establish a consistent transformation procedure between the time reference systems of the selected datasets.

b. Resolution

Time resolution is defined as the smallest time unit used for recording the time information (Peuquet, 1999). The selection of resolution is purely dependent on the application, e.g., the statistical data often uses year, season or month, while the resolution of IoT observation may be second or even milliseconds. The risk increases when dealing with datasets whose valid time are recorded with different level of resolution because the interpretation of valid time becomes rather complicated for time information based on lower levels of resolution.

c. Geometric Primitive

From the geometric perspective, ISO 19108 defines two concepts of time representation: time instant and time period(Figure 2). Both the class of TM_Instant and TM_Period inherits from the class of TM_GeometricPrimitive (ISO, 2002) and can be used for modelling the temporal status of a dataset or even a feature. The time information described by the class of TM_Instant refers to a single point on the time axis, while those modelled with the class of TM_Period refers to a continuous time interval defined by two time instants with semantics of beginning and ending. For datasets whose content is acquired within a very short period of time (e.g., remote sensing images), time instant is often used. On the other hand, if the content of datasets remains unchanged for a period time and the time of change can be precisely determined (e.g., cadastral system), then time period is used. This time modelling concept has been widely used in various ISO/TC211 and OGC standards, e.g., CityGML3.0(Consortium, 2021).

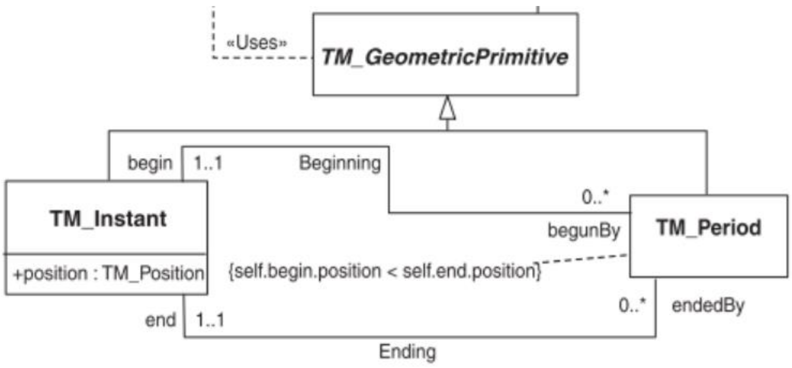


Figure 2. Temporal geometric primitives (ISO 19108, p.9).

d. Semantics

Attributes designed for recording time information have their respective purposes, e.g., the time the data is colleced, the time the application is submitted, the time the land is registered. Time information is meaningful only when correct ”semantics” is provided. The ”valid time” concept proposed in this research basically follows the ”world time” concept from Hsiou (2010), which implies the time the data is collected(Xiao Shilun, 2010). It is then reasonable to assume that the data content is valid to represent the earth phenomena at this specific time. However, since the status may last for a period of time, this concept has to be extended and not only limited to the collection aspect. For application schema design, time information that can be included is certianly not restricted to ”valid time” only, every attributes must be defined with appropriate semantics to ensure the data can be correctly interpreted in their respective applications. Among the various terms that can be used for modelling the time semantics (refer to ISO19115), it is advantageous to define a set of commonly used vocabularies, such that the time information of cross-domain dataset can be processed with a comprehensive and consistent manner. Standards of time ontologies are possible solution for handling the time semantic heterogeneity issues(Bittner, Donnelly, & Smith, 2009).

e. Topology

The early research for topology of time can be traced back to the seven relationships between time intervals, namely, meet, overlap, before/after, start, finish, equal, and during(Allen, 1983). The proposed topological relationships were proposed with formalized mathematic properties and semantics that can be applied to human daily lives. Since the major focus of this research is to examine if the selected datasets can work together, the topology between the valid time of the selected datasets serve as an important reference. From a geometric perspective, the intersection of the valid time of the selected datasets implies the corresponding phenomena of the selected datasets simultaneously exist, i.e., the valid time of the operation outcomes. If we are dealing with features with different valid time, the determination of topology must be further extended to the level of feature, which will make the analysis even more complicated. Furthermore, since the valid time may be represented by time instant, the topological model also need to be extended for considering the possible topological relationships related to time instant.

3.2 Time-aware GIS operation analysis

GIS operations are designed to process or derive the required data according to the application needs. From the design perspective, every GIS operation follows a pre-defined algorithm or workflow to work with the selected data, the process behind the interface thus control the outcomes. Regardless of professional or not, uses often lack the knowledge about the presumption and limitation of the GIS operations, hence they tend to process the selected datasets without seriously considering even the most fundamental requirements. Some GIS operations are even only designed with naïve consideration. The quality-aware research discussed in section 2 represents the various thinking by taking data quality aspect into the GIS operation design, such that the impacts from the data quality of the datasets can be comprehensively handled and presented with care. The following further explore 4 GIS operations that require to take temporal aspect into their design strategies.

a. Map overlay: Map overlay typically works on a spatial basis that process all the datasets to refer to the same coordinate reference sysem, so as to provide an overall locational distribution in a map fashion. Since temporal aspect is seldom considered, overlaying datasets without noticing their time difference may frequently happen. Although this does not necessarily mean the overlaid results is not meaningful and some applications even do it on purpose (e.g., change detection), the risk of wrong interpretation still exist. To be seen as a map, the valid time of the overlaid outcomes have to be determined based upon the geometric intersection of the valid time of the selected datasets. Users should be at least made aware of the difference of valid time for the selected datasets and overlaid outcomes to avoid wrong decision.
b. Spatial operators: The outcome of many GIS operations is based on the location of selected features. When the shape and size of the features change with time, it becomes necessary to further link time information with the outcome. For example, the buffer opeation create a buffered area based on the geometry of the selected feature. While the operation itself is a purely spatial operator, the correct interpretation has to consider the static/dynamic characteristics and the valid time of the reference features. Any further process, e.g., querying features within the buffered area, is hence also time-dependent (i.e., the valid time of the queried objects must be also considered.). Spatial operations that involve more than two datasets, e.g., intersection, dissolve, union, clip and difference, also need to consider the difference between their valid time.
c. Digitization: The digitization operators allows uses to create new data based upon a reference datasets, e.g., satellite images. While this is again an operation purely based on the location aspect, the valid time of the newly created data should refer to the valid time of the reference datasets. Failure to establish the necesary temporal links with the reference datasets impedes the correct use of the digitized datasets. The valid time of the digitized datasets also serve as the judgement reference in the map overlay operations.
d. Join: The join operation connects two datasets according to the spacified conditions. For example, the same ID can be used to connect cross-domain data for the same feature. However, since the status of an indivisual feature may change with time and identified by

the same ID, the joined results will likely include attribute values respectively referring to two differnt valid time. It becomes much more complicated to describe the valid time of the outcomes. Similar situations also happen to spatial join operations. When a specific topological relationship is given, the qualified features are only meaningful if the valid time of the involved datasets meets the ”simultaneous existence” presumption. Any dataset or feature without valid time description will increse the risk of correct interpretation about the joined outcomes.

3.3 Time-aware GIS Operation Design

Through the standardized temporal description framework, both the data provider and the user realize the time information of the data, and can specifically evaluate its operational risk. The time-aware operations can be inferenced first by determine the valid time of each phenomenon, and then use the topology relationship to check whether the valid time periods of each phenomenon have an intersection topology relationship. Different topology relationship conditions can explain different situations, for example whether it is raining during the marathon, if the relationship between the two time periods is before/after, it means that there is no rain during the marathon; if it is overlap, during, start, finish, it means that the marathon is affected by rain. Therefore, the development of the time-aware system is based on valid time inference, identifying risky interpretation first, preventing users from accepting unreasonable visualize results, and providing an intelligent operation interface. The time-aware system is based on the topology conditions predefined. Through good resource and service management, planning, organization and interface design, it should provide an easy and intuitive interface for users to obtain decision reference information provided by the system without additional professional analysis.

The data input to the time-aware system must meet the basic requirement of the standardized temporal attributes. The data is provided to the user for analysis and operation under the description of the standardized time framework, and the final result provided has the ability of time awareness. Each dataset must have a valid time description, and related operations must allow valid time to be intersected for each dataset, and the applicable interpretation of the result comes from the intersection of all valid time periods. Using the basic time recording elements planned in the previous sections and the condition setting of the topological relationship, there is a specific topology according to different recording primitives, and the system establishes related operations based on the infer of the valid time. AsTable 1shows, the specific relationship can be summarized as follows in three categories, different situations, and then set different topology conditions:

Table 1. Valid Time of different primitive.

Primitive	Topology	Valid Time
Time stamp vs. time stamp	Equal	Yes (The time point)
	Before/ After	No
Time stamp vs. time period	Before/ After	No
	Start	Yes (The start time)

	Finish	Yes (The end time)
	During	Yes (The time during the period)
Time period vs. time period	Before/ After	No
	Meet	No
	Start	Yes (From the same start time point of the two states to the end of the state with the shorter occurrence time)
	Finish	Yes (From the state that occurs later to the end of the same time point of the two states)
	During	Yes (Simultaneous occurrence of two states)
	Overlap	Yes (Only overlap period)
	Equal	Yes (From the start to the end)

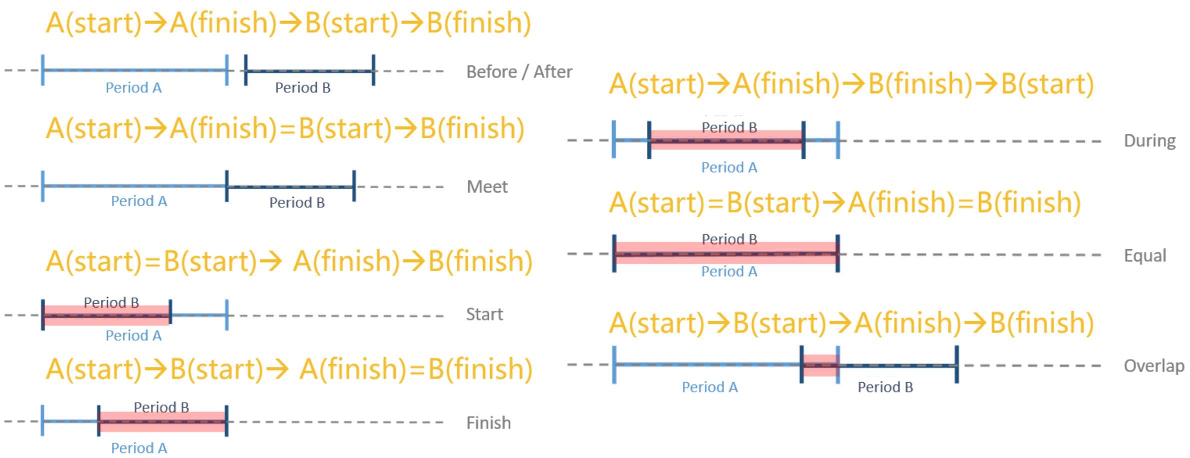


Figure 3. Valid time of time period vs. time period (red part).

The time-aware system uses the description of the aforementioned standardized time description, Table 1 summarized all situations. Based on the primitive definition, the developed system must determine the valid time according to the specific situation of the operation outcome. As Figure 3 illustrates that the results explained in the red interval are valid because the valid time periods of the two phenomena have an intersection relationship.

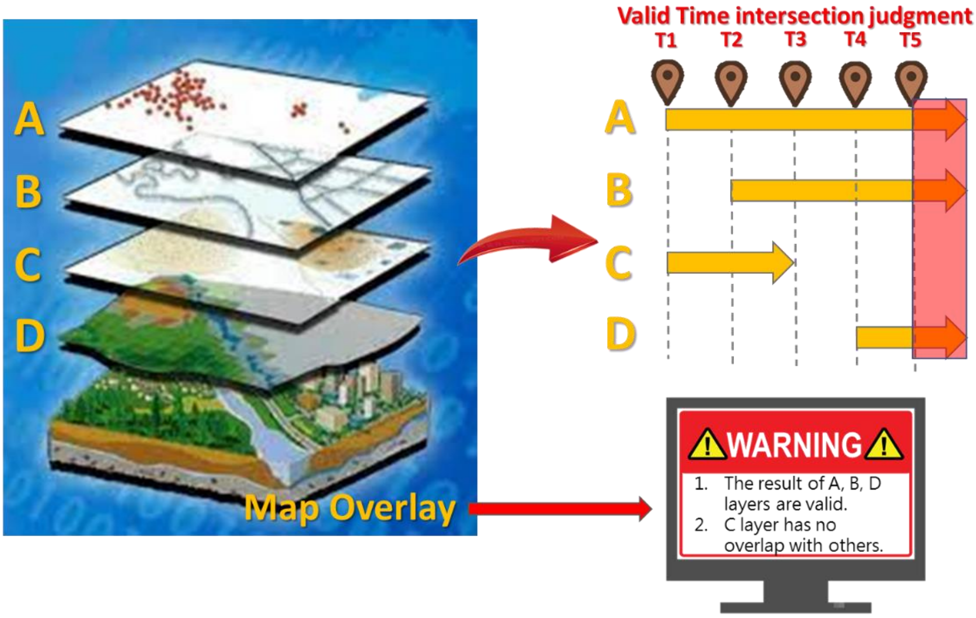


Figure 4. Time-aware System operation (Map Overlay).

As shown in Figure 4, when users are operating GIS functions, the system automatically analyzes the existing risks and chooses a more suitable visualization result. At the same time, based on the topology inference, it can be aware of the valid time of the selected datasets is not intersected. Therefore, the time-aware system can propose potential risks of current results to warn the user or even suggest better strategies, as shown in the lower right corner of Figure 4, a warning message will appear on the system interface to warn the user that layer C has no valid time intersection with other layers.

4. Scenario analysis

Take Taiwan e-Map as an example, Taiwan e-Map has many overlapping layers provided by different units, including various information such as buildings and roads (Figure 5). When doing map overlay, all the selected datasets have their respective valid time, if the users do not pay attention to the valid time issue, it may lead to wrong interpretation. Table 2 shows the actual situation of the parcels, roads and buildings in each time period.

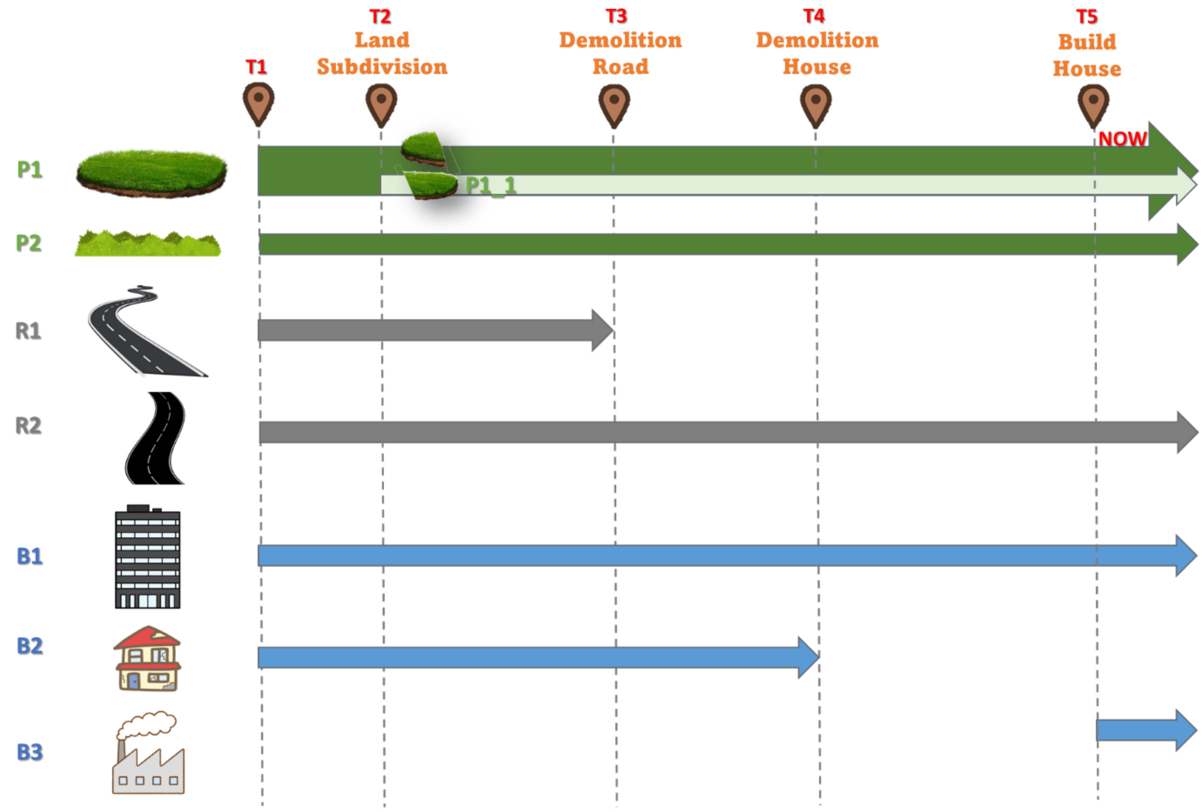
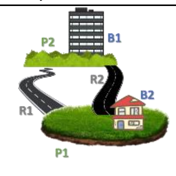
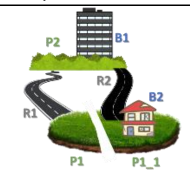
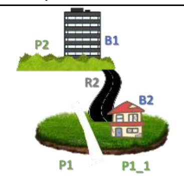
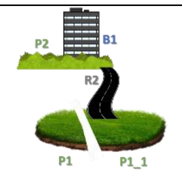
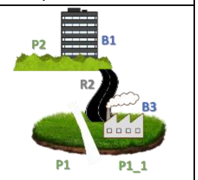


Figure 5. Valid time of layers in Taiwan e-Map

Table 2. The situation at each time point.

	T1	T2	T3	T4	T5
Parcel	P1, P2	P1, P2, P1_1	P1, P2, P1_1	P1, P2, P1_1	P1, P2, P1_1
Road	R1, R2	R1, R2	R2	R2	R2
Building	B1, B2	B1, B2	B1, B2	B1	B1, B3
Diagram					

As Figure 6 illustrates, in this case, the time of the parcels, roads, and building layers have their own validity period, but the temperature observation records the data at a time instant. The valid time period of all features is different when performing visual display, Figure 7 is the final visualization result, which eventually leads to errors in the results, for instance, it is impossible for R1 and B3 to appear on the map at the same time. Table 3 shows the correct visualization results of the overlapping situation in each time interval.

Through the time-aware system, the following information is provided to the user: The screen display of a wrong result since the valid time of all features does not intersect. The recommended map overlay strategy is shown in Table 4.

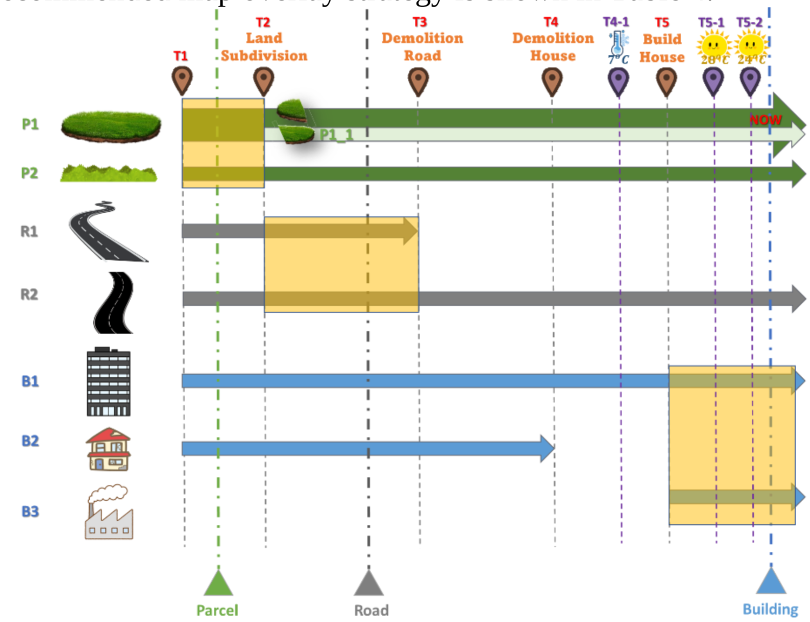


Figure 6. The situation of valid time intersection of each layer.

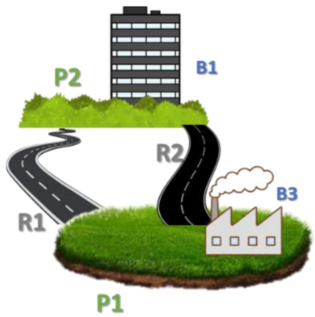


Figure 7. Result of map overlay.

Table 3. Overlapping situation in each time interval.

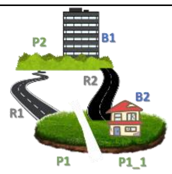
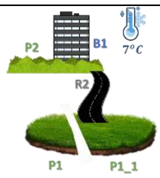
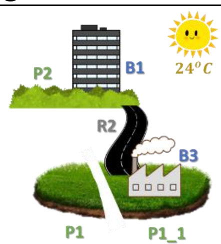
	T1~T2	T2~T3	T3~T4	T4~T5
Parcel	P1, P2	P1, P2, P1_1	P1, P2, P1_1	P1, P2, P1_1
Road	R1, R2	R1, R2	R2	R2
Building	B1, B2	B1, B2	B1, B2	B1
Temperature	No Data	No Data	No Data	7^oC
Diagram				

Table 4 Recommended map overlay strategy.

	Time: NOW	Diagram
Parcel	P1, P2, P1_1	
Road	R2	
Building	B1, B3	
Temperature	24^oC	
	The temperature observation points with a temperature of 28 degrees Celsius and a	

	temperature of 24 degrees Celsius both fall within the valid time period. But the observation time of 24 degrees Celsius is the latest time.	

5. Conclusions

The record of time information is an important and necessary content for geographical data, whether and how to record time information will also affect the subsequent analysis and application. The three-dimensional space data structure with time can solve many real-world simulation problems. However, this will require the establishment of correct spatial-temporal status. Time is one of the considerations that people often ignore when doing GIS analysis. This paper presents a temporal recording framework for making GIS operations time aware. From the point of view of the integrated operation of geographic information, the time description of geographic data can avoid wrong judgments and can connect different time versions through identification attributes. A time-aware system can allow users to achieve better results without special ability to interpret time, and provide suggestions that allow users to interpret correctly. The findings of this standardized temporal description framework developed in this study have been successfully applied to map overlay case and can provide the basis for the development of time-aware systems. In addition to enhancing the correctness of the GIS operation results, time awareness can also consider the quality of the fitness of the spatial results.

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